Investigation of the Axial Load Transfer Mechanism within Cast-In-Steel-Shell Piles

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ABSTRACT
In this experiment, the axial load transfer mechanism in Cast-In-Steel-Shell (CISS) Piles was investigated. Twenty-one CISS pile test units were tested, with typical diameters of 610 mm, and diameter to thickness (D/t) ratios ranging from 24 to 128. Several load transfer mechanisms were studied, which included a: shear ring, welded bar, weld bead, shear studs, cross bar, and tread plate. Other parameters studied in this experiment included the effects of: shear ring spacing, D/t ratio, expansive concrete, and surface condition. Test units were subjected to a quasi-static reversed cyclic axial loading. All load transfer mechanisms exhibited a noticeable increase in the axial load capacity, in compression and tension. Test units with a mechanism circumferentially welded to the steel shell (i.e. shear ring) had the best performance. Such mechanisms were effective to the extent that the confinement pressure, provided by the steel shell for test units with a high D/t ratio (128 and 96) was exceeded. This resulted in an out-of-plane deformation of the steel shell at the shear ring location. Test units with a higher confinement pressure (D/t ratio of 24) resulted in a crushing failure of concrete at the mechanism location. Results from this experiment will be presented.

INTRODUCTION
Cast-In-Steel-Shell (CISS) pile foundations, also known as drilled piers with permanent steel casing, consist of a circular steel shell section filled with reinforced concrete. The California

Department of Transportation (Caltrans) uses this construction technique in bridge foundations, with diameters typically ranging from 0.6 to 3 m, and pile lengths in some cases exceeding 100 m. Some of the concerns designers have with CISS piles include the composite bond between the steel shell and concrete core, the effectiveness of axial load transfer mechanism designs, and the shrinkage potential of the reinforced concrete core. The usage of axial load transfer mechanisms, such as shear rings, can provide a high level of axial load transfer and have been used by Caltrans in many bridge foundations, including the new east span of the San Francisco-Oakland Bay Bridge.

CISS piles must resist not only the dead load of the superstructure, but also seismic load in both horizontal and vertical directions. When bridge structures are subjected to seismic loading, the superstructure will undergo cyclic displacements in the transverse and longitudinal directions. As an abutment or bent is displaced cyclically in the lateral direction, its pile foundation will be subject to moment reversals. This moment reversal can cause the pile loading to alternate between tension and compression. Such loading, could result in a bond separation between the reinforced concrete core and the steel shell, provided the steel shell has adequate resistance with the soil. In some design cases, the steel shell is twice the length of the concrete core, thus providing a large surface area in contact with the soil for load transfer (i.e. uplift resistance).

EXPERIMENTAL PROGRAM

The experimental program consisted of six test units to study axial load transfer mechanism designs, five test units to study the effect of the D/t ratio, three test units to study the effect of expansive concrete with the D/t ratio, and one test unit to investigate the interface condition. In a second phase of testing, six test units investigated the shear ring design, particularly the role of ring spacing, and the effect of the D/t ratio. Details for the experimental program are listed in Table 1. A concrete mix design with an $f_c^{'}$ of 14 MPa, at 28 days, was specified to ensure strength on the day of test would not exceed 21 MPa. If the concrete strength exceeded this value, then the resulting load

Unit #	Steel Shell D (mm), t (mm), D/t	Axial Load Transfer Mechanism: Type, Quantity	Axial Load Transfer Mechanism: Dimensions (mm)
1	610, 4.8, 128	None	
2	597, 6.4, 96	None	
3	584, 12.7, 48	None	
4	610, 4.8, 128	Weld Bead, 1	3.2
5	610, 4.8, 128	Shear Ring, 1	12.7 x 12.7
6	610, 4.8, 128	Cross Bar, 1	50.8 x 25.4
7	610, 4.8, 128	Welded Bar, 1	12.7 diam
8	610, 4.8, 128	Shear Studs, 21	12.7 diam
9	610, 4.8, 128	Tread Plate, 1,700	
10	610, 4.8, 128	Tremmie Pour	
11	387, 9.5, 42.7	None	
12	387, 9.5, 42.7	None	
13	610, 4.8, 128	Expansive Concrete	
14	597, 6.4, 96	Expansive Concrete	
15	584, 12.7, 48	Expansive Concrete	
16	610, 6.35, 96	Shear Ring, 1	6.35 x 12.7
17	610, 25.4, 24	Shear Ring, 1	6.35 x 12.7
18	610, 25.4, 24	Shear Ring, 1	6.35 x 12.7
19	610, 25.4, 24	Shear Ring, 2	6.35 x 12.7 @ 76
20	610, 25.4, 24	Shear Ring, 2	6.35 x 12.7 @ 152
21	610, 25.4, 24	Shear Ring, 2	6.35 x 12.7 @ 305

Table 1 Experimental Program

transfer mechanism strength (under axial tension load) would potentially reach the ultimate strength of the longitudinal reinforcement; a highly undesirable outcome.

All test units had a void in the core, with a 127 mm height, located at the base of the steel shell to ensure that axial load was transferred only through surface bond and through axial load transfer mechanisms during the test. At the top of each test unit, a reinforced concrete load transfer section extended 762 mm beyond the steel shell to allow compressive and tensile load from the test setup to fully develop in the reinforced concrete prior to its transfer to the test region bounded by the steel shell.

A typical 0.61 m diameter test unit was reinforced with a 508 mm external diameter bar cage with longitudinal reinforcement provided by ten No. 11 bars, resulting in a reinforcement ratio of 3.4%, as shown in Figure 1. Confinement was provided by a No. 4 spiral with a pitch of 152.4 mm for the reinforcement bar cage section within the steel shell.

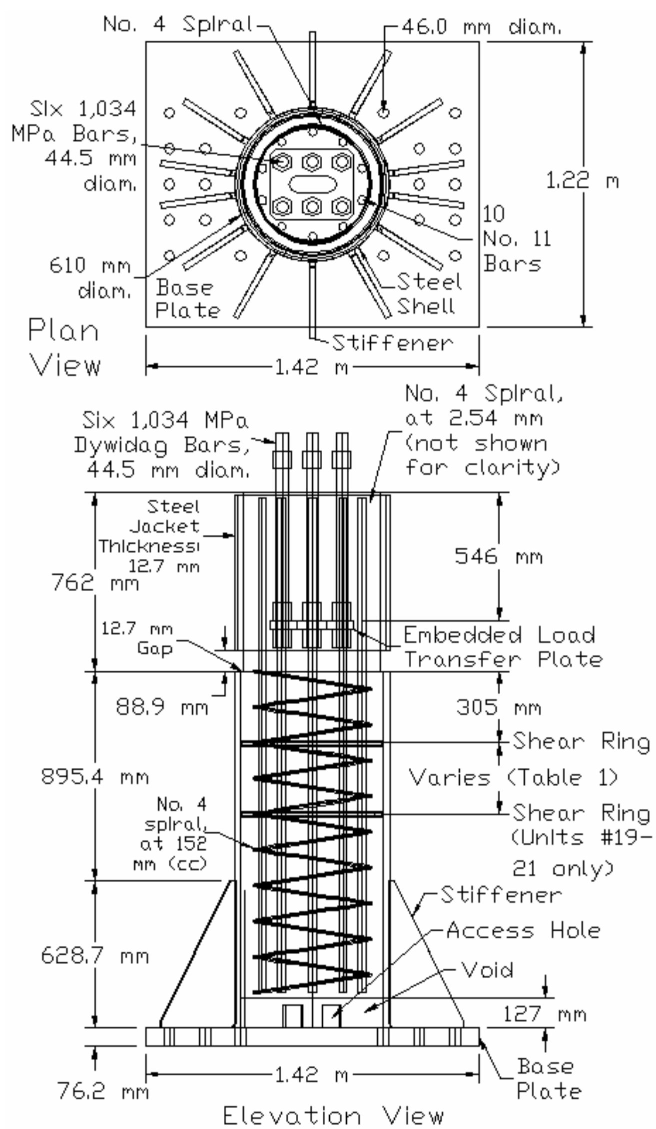

Figure 1 Typical Test Unit

Test Unit Reactions

The transfer of axial tension load at the top of each test unit was obtained with six high strength 1,034 MPa, 44 mm diameter bars. These bars were fastened to a plate and embedded in the reinforced concrete core as shown in Figure 1. Axial compression load was applied directly to the top of the reinforced concrete core load transfer section. No axial load was applied directly to the top of the steel shell. At the base of the test unit, axial load was transferred only though the steel shell. The base reaction consisted of a steel base plate and welded stiffener plates (A572 grade 50). Base plates had a hole pattern corresponding to the test setup, to allow for a post-tensioned connection. Additional details for the test unit design are discussed in Gebman, et al (2004) for test units # 1-15 and Gebman et al (2005) for test units # 16-21.

Axial Load Transfer Mechanisms

Six different axial load transfer mechanisms were tested as part of this study. Three of the mechanisms were designed to fit the internal diameter of the steel shell. Each of these three mechanisms were welded at 0.3 m from the top of the steel shell, as shown in Figure 1. A single steel shear ring was used in Test Unit # 5, and had a cross section with a dimension of 12.7 mm square. A single circumferentially welded reinforcement bar (No.3) was used in Test Unit # 7, and had a diameter of 12.7 mm. These two mechanisms were welded to the steel shell with a continuous 4.8 mm fillet weld along the top face. The third mechanism, in a circumferential plane, consisted of a single weld bead with a size of 3.2 mm and was used in Test Unit # 4. Test Unit # 6 had a single cross bar placed inside the reinforcement cage to span the internal diameter of the steel shell. The cross bar had a cross section with a height of 50.8 mm, and a width of 25.4 mm. A vertical 4.8 mm fillet weld, connected the cross bar ends to the uppermost steel shell section, as shown in Figure 2. Twenty-one shear studs were placed inside the steel shell, of Test Unit # 8, in an arrangement of three circumferential rows with seven studs evenly distributed per row. Studs were placed with a 76.2 mm vertical spacing and a 274.3 mm radial spacing. The uppermost row was at 0.3 m from the top of the steel shell. Studs had a length of 28.6 mm and a head diameter of 12.7 mm, as shown in Figure 2. A tread plate with approximately 1,700 treads was rolled to form the upper steel shell section (0.46 m height) of Test Unit # 9.

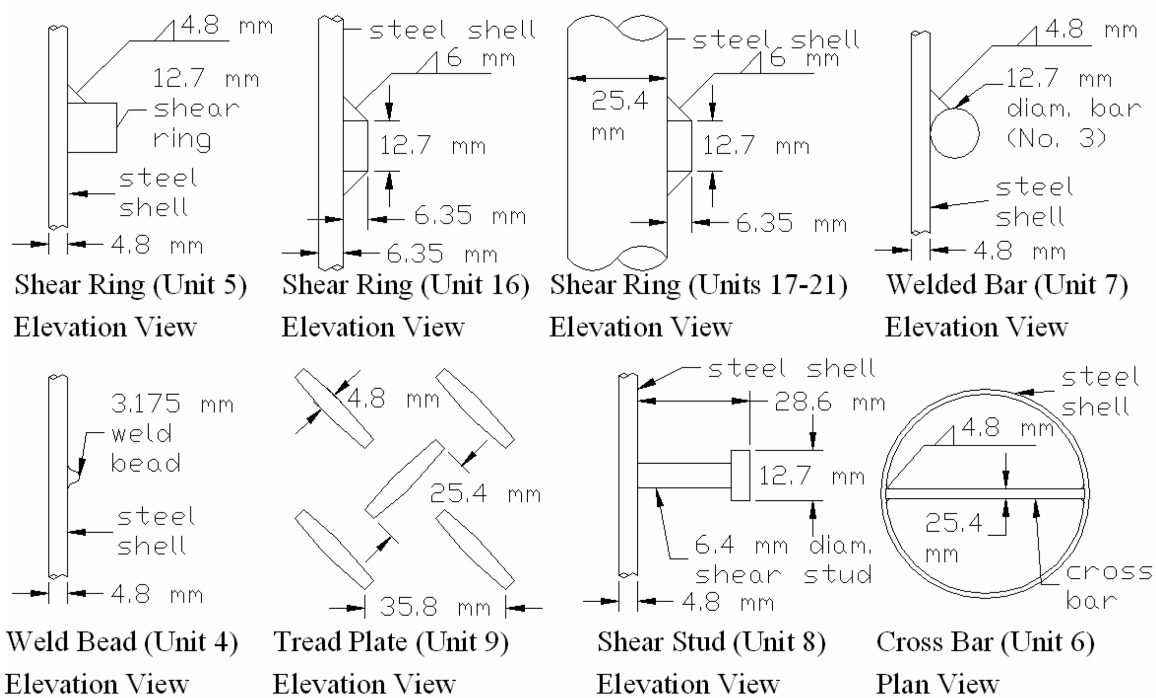

Figure 2 Axial Load Transfer Mechanisms Tested

Other Parameters Investigated (D/t Ratio, Expansive Concrete, and Surface)
The effect of the D/t ratio was investigated with five test units. Three test units had an internal diameter of 0.61 m and shell thicknesses of 4.8 mm, 6.4 mm, and 12.7 mm, respectively. This resulted in D/t ratios of 128, 96 and 48. A D/t ratio of 42.7 was simulated in two test units with an internal diameter of 0.39 m and a shell thickness of 9.5 mm. Three test units with a diameter of 0.61 m and steel shell thicknesses of 4.8 mm, 6.4 mm and 12.7 mm were constructed using an admixture (CTS Komponent) to produce an expansive concrete. Komponent was added at a quantity of 53.4 kg per 1.0 m^3 of concrete. The effect of a “tremmie pour” in which a drilling fluid is present within the steel shell, was studied, in Test Unit # 10, by coating the interior steel

shell and the reinforcement bar cage with a water-bentonite mixture just prior to placement of the concrete. Results for these test units can be found in Gebman, et al (2004).

Shear Ring Test Units – Second Phase of Testing

To evaluate the effectiveness of shear rings at transferring axial load to the steel shell, six 610 mm diameter test units were tested, as listed in Table 1. The shear rings, for Test Units # 16-21, had a radial thickness of 6 mm, a height of 13 mm and were fabricated from ASTM 572 Grade 50 hot rolled flat bar bent to fit the internal diameter of the steel shell. Shear rings were welded along the top and bottom of the ring with a 6 mm fillet weld. Test Unit # 5 had a 13 mm square cross section shear ring with a 6 mm weld along the top. Figure 2 shows details for the shear rings. Test Units # 5, # 16, # 17, and # 18 had a single shear ring welded at 305 mm from the top of the steel shell.

The steel shells for Test Units # 17-21 had a diameter of 610 mm, and a thickness of 25 mm, resulting in a D/t ratio of 24. The steel shell for Test Unit # 16 had a diameter of 610 mm, and a thickness of 6.25 mm, resulting in a D/t ratio of 96. Test Units # 16 and # 17 investigated the effect of D/t ratio on the shear ring transfer mechanism force. Test Unit # 18 was similar to Test Unit # 17, however, a polyethylene lining was placed inside the steel shell to prevent bond between the concrete core and the steel shell. Test Units # 19-21 had two shear rings, as shown in Figure 1, and were tested to investigate the influence of spacing between shear rings on the capacity and hysteretic response. The center-to-center spacing between shear rings in Test Units # 19-21 was 76, 152 and 305 mm, respectively.

Test Protocol

A reversed cyclic axial load was applied quasi-statically to each test unit, using the UCSD-Caltrans Seismic Response Modification Device (SRMD) Test Facility. The SRMD is a displacement controlled system; hence a displacement based test protocol was used. The protocol consisted of eight displacement levels, each with three cycles in axial compression and axial tension. Displacement levels consisted of target displacements of ± 2.54, ± 5.08, ± 7.6, ± 12.7, ± 25.4, ± 50.8, ± 76.2, and ± 101.6 mm. The maximum axial load capacity of the test setup, in compression and tension was 8.9 MN. Test units were placed in the test setup in a horizontal orientation.

EXPERIMENTAL RESULTS

Test Unit # 5

Test Unit # 5 had a single shear ring within a thin steel shell (D/t ratio of 128). This steel shell confined the reinforced concrete core at the shear ring location; however, the axial load transfer through the shear ring mechanism exceeded the confinement strength provided by the steel shell. This resulted in the steel shell deforming in the out-of-plane direction, with a radial deformation of approximately 9.5 mm, and a height of approximately 305 mm, as shown in Figure 3. Inside the steel shell, concrete above and below the shear ring crushed in a circumferential region corresponding to the steel shell deformation height. The radial depth of concrete crushing did not go beyond the shear ring. A maximum axial compression load of -3,093 kN at -50.7 mm was obtained after which the axial compression load increased due to contact between the steel base plate and reinforced concrete core, as shown in Figure 4. This contact was due to failure of concrete at the base of the reinforced concrete core, which accumulated to the extent that the base void became partially filled. In axial tension, this test unit obtained a maximum axial load of 3,481 kN at a displacement of 24.1 mm. A comparison of the hysteretic response of this test unit to that of Test Unit # 1 (D/t = 128, no shear ring) is presented in Figure 4. This figure clearly shows the increase in axial load transfer gained through a single shear ring, despite an out-of-plane failure of the steel shell.

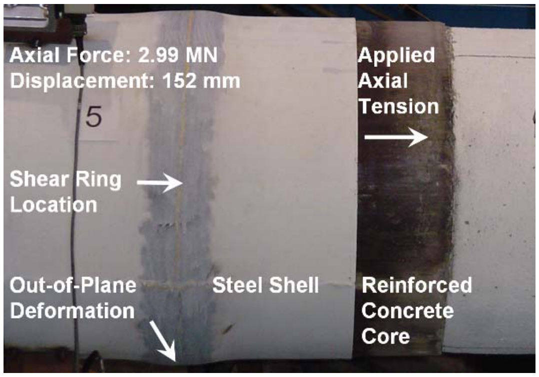

Figure 3 Out-of-Plane Deformation in the Steel Shell of Test Unit # 5 (D/t = 128) – at a Displacement beyond the Test Protocol

Test Unit # 17

Test Unit # 17 had a single shear ring within a steel shell with a D/t ratio of 24. The high confinement pressure provided by the steel shell resulted in a concrete crushing failure within the reinforced concrete core, at the shear ring location. No out-of-plane deformation occurred in the steel shell, at the shear ring location. Strains on the steel shell, in both the longitudinal and transverse directions did not exceed yield. This test unit obtained high levels of axial load transfer, which continued to increase as displacement levels increased, as shown in Figure 4. Axial tension loading did not exceed 4,370 kN, at a displacement of 16.5 mm, due to spalling of reinforced concrete in the load transfer section of the test unit. This was a result of the longitudinal reinforcement bars exceeding the yield strength. After this maximum axial tension load, the test unit was loaded in monotonic axial compression to a displacement of -44 mm, and an axial load of -6,040 kN, when the test had to be stopped for safety reasons. At this displacement, the test unit was still increasing in axial compression load. The hysteretic behavior of this test unit is shown next to that of Test Unit # 5 with a D/t = 128 (and a slightly larger shear ring), in Figure 4, to compare the two aforementioned failure mechanisms.

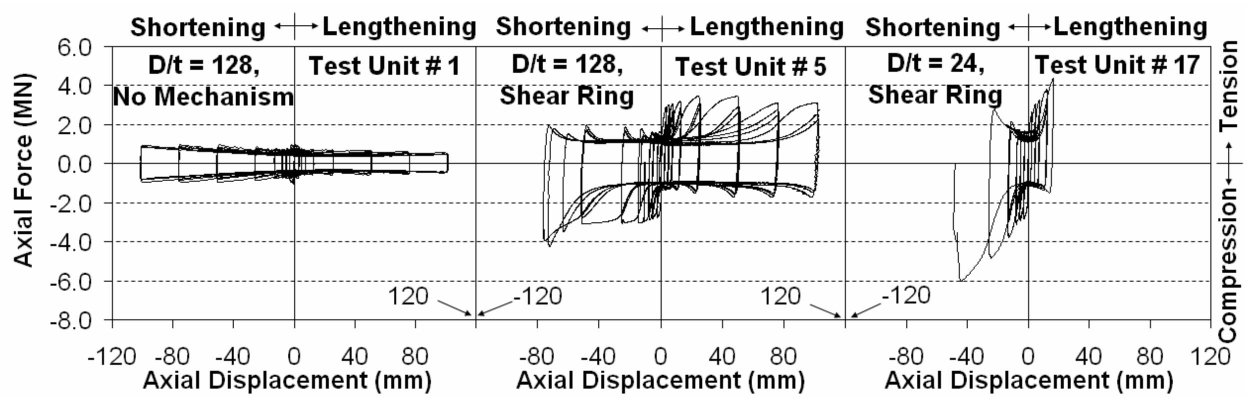

Figure 4 Hysteresis Response for Test Unit # 1 with no Shear Ring and D/t = 128 (left), Test Unit # 5 with a Shear Ring and D/t = 128 (middle), and Test Unit # 17 with a Shear Ring and D/t = 24 (right)

Load Transfer Mechanism Performance Comparison

As discussed in previous sections, six load transfer mechanism designs were tested, all of which exhibited a noticeable increase in axial load. Mechanisms with a substantial weld contact area with the steel shell, such as the shear ring, welded reinforcement bar, and weld bead were able to maintain high levels of axial compression and tension load transfer at all displacements. Figure 5 shows a comparison of the performance envelopes for all load transfer mechanisms tested. These envelopes were generated from the peak cyclic loads at each displacement level. The shear stud mechanism and cross bar both had small weld contact areas, which resulted in a shear failure at the weld at low displacements. This reduced the axial load transfer at greater displacements, as shown in Figure 5. The tread plate mechanism initially obtained high axial loads, however, the axial load transfer decreased at greater displacements, as the concrete between treads failed hence reducing the number of treads actively in contact with the reinforced concrete core. The shear ring and welded bar behaved similarly (both had the same area protruding into the core) and maintained high axial load transfer despite the formation of an out-of-plane deformation in the steel shell.

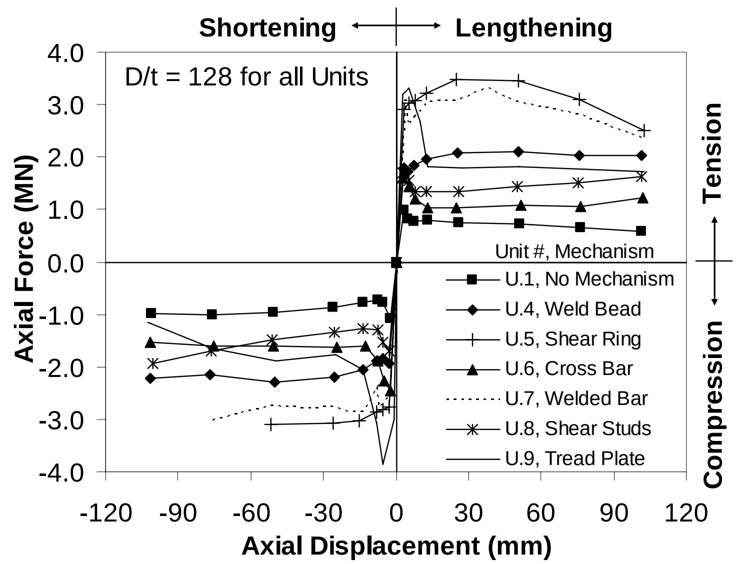

Figure 5 Performance Comparison for Axial Load Transfer Mechanisms

Comparison of Shear Ring Test Results

A comparison of the response of test units with shear ring(s) was made by plotting the performance envelopes, as shown in Figure 6, and as defined in the previous section. Test Unit # 18, with the plastic lining, had the lowest axial tension loads at the first four displacement levels, as shown in Figure 6. This test unit had moist concrete present at the shear ring location as revealed after the experiment, and discussed in Gebman, et al, 2005. This test unit ultimately obtained higher axial loads than Test Unit # 16 with a D/t = 96, which failed through an out-of-plane deformation of the steel shell at the shear ring location. The deformation in Test Unit # 16 resulted in relatively constant axial loads at higher axial displacements (Figure 6). Test Unit # 19, with a shear ring spacing of 76 mm, had a slightly improved performance when compared to Test Unit # 17, with a

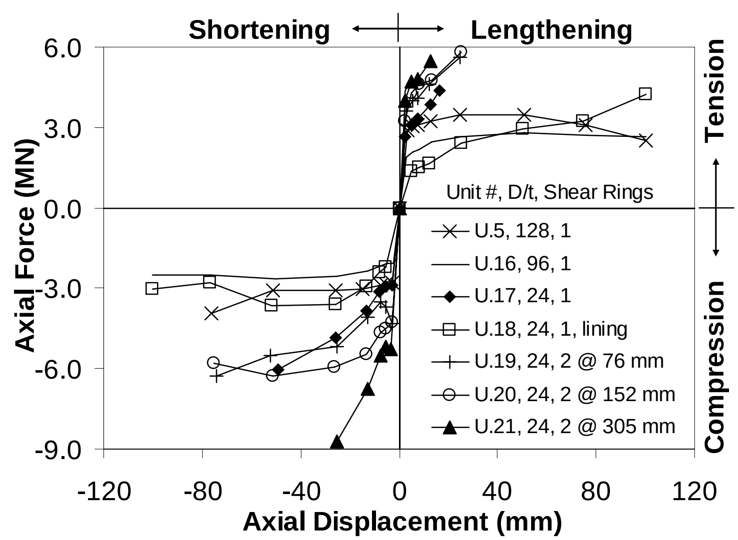

Figure 6 Performance Comparison for Test Units with one or two Shear Rings

single shear ring. As the shear ring spacing increased to 152 mm, (Test Unit # 20) the performance improved, despite the presence of moist concrete at the shear ring location, in this test unit. At a shear ring spacing of 305 mm, a further increase in axial loads was obtained, such that no axial compression displacements beyond -25 mm could be simulated as the test setup capacity was nearly obtained. This shear ring spacing was clearly the most effective, because the shear rings were spaced far enough apart such that each shear ring behaved individually. After the experiment, the steel shells were removed from the reinforced concrete core. This revealed a vertical concrete failure plane between the shear rings of Test Unit # 19. Concrete between the shear rings of Test Unit # 21 remained in tact, as shown in Figure 7.

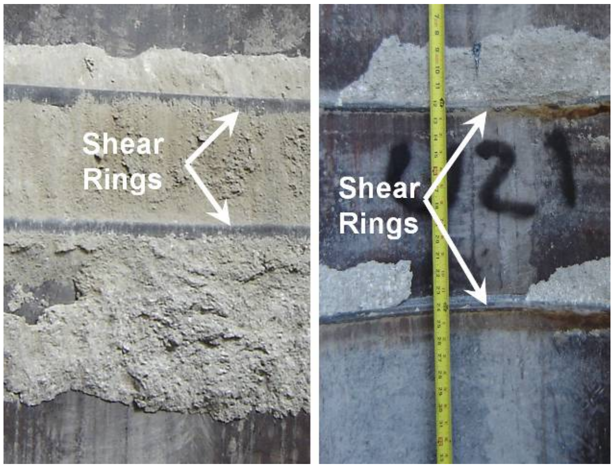

Figure 7 Comparison of the Failure of Reinforced Concrete at Shear Rings: Test Unit #19 with a Spacing of 76 mm (left) and Test Unit #21 with a Spacing of 305 mm (right)

CONCLUSIONS

This experiment has provided a much needed insight into the performance of axial load transfer mechanisms within CISS piles. Experimental results have already influenced and benefited CISS pile designs.

In this experiment, three failure modes for CISS piles with axial load transfer mechanisms were found, which consisted of:

1. Shear failure of the mechanism connection to the steel shell for mechanisms with a small contact area with the steel shell.
2. Out-of-plane deformation of the steel shell at the mechanism location, for high D/t ratios (96, and 128)
3. Concrete crushing above and below the mechanism for a low D/t ratio (24)

Ongoing analysis of the experimental data and a finite element model (using ABAQUS) will provide final design recommendations.

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